Illuminating semiconductors with optical-vortex light

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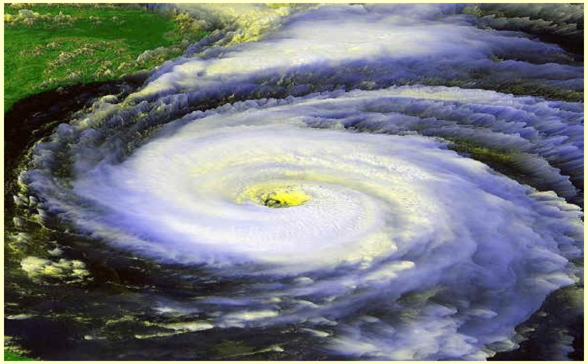
Argentina

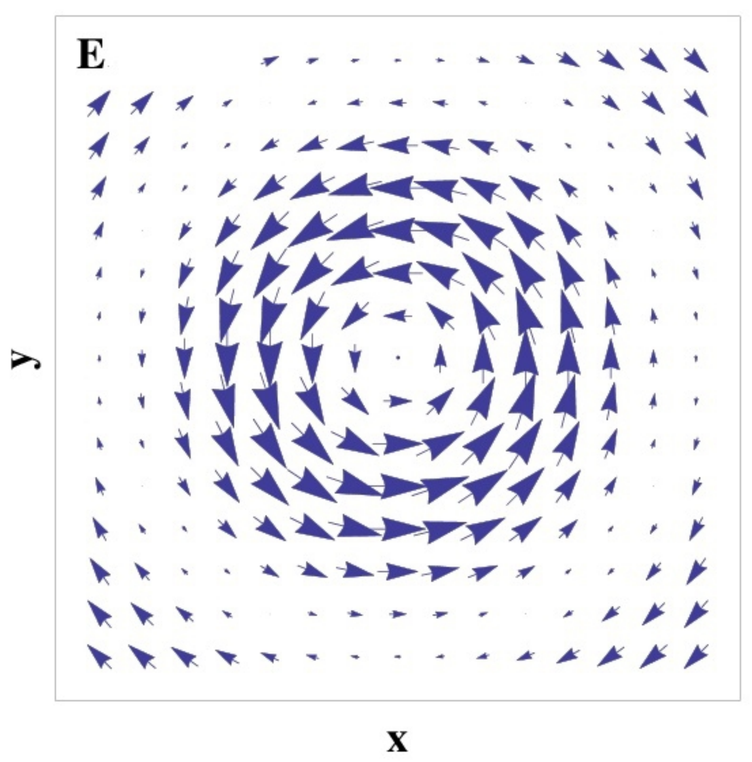
Optical-vortex light ?

It evokes images of



… and is indeed something like this.

It is highly inhomogeneous light having a vortex or phase singularity in its axis, where the electric and/or magnetic fields can be zero.



A comment on nomenclature...

Optical-vortex light = Twisted Light

and also:

Light carrying orbital angular momentum

Mathematical representation

$$\overline{E'}(r,\varphi,z;\omega)=\overline{E}(r,\varphi)\mathrm{e}^{i(\omega t-kz)}$$

Paraxial optical-vortex

$$\overline{E}(r,\varphi)=\underbrace{\overline{\epsilon}_{\pm}}_{\text{Circular polarization}}\overbrace{e^{\pm i\ell\varphi}}^{\text{Vortex}}\underbrace{F(r)}_{\text{Radial profile}}$$

Polarization: Spin angular momentum $\pm\hbar$

Vortex: Orbital angular momentum $\pm\hbar\ell$

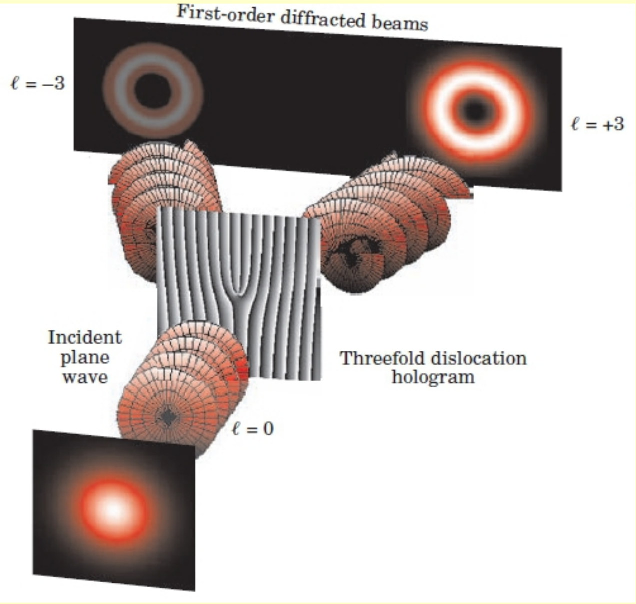
… and non-paraxial beams?

$$\overline{E}(r,\varphi)=\bar{\epsilon}_{\pm}\,\mathrm{e}^{\pm i\ell\varphi}F_1(r)+\underbrace{\hat{z}\,F_2(r)\,\mathrm{e}^{\pm i(\ell\pm1)\varphi}}_{\text{Longitudinal component}}$$

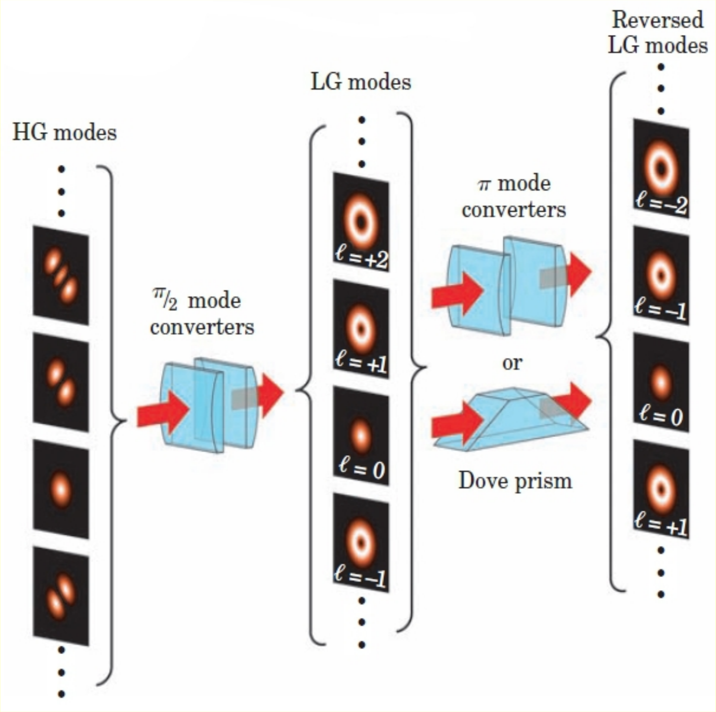
These beams can be produced by focusing a non-paraxial beam

Strong magnetic fields near the phase singularity may exist

Generation of paraxial optical-vortex beams

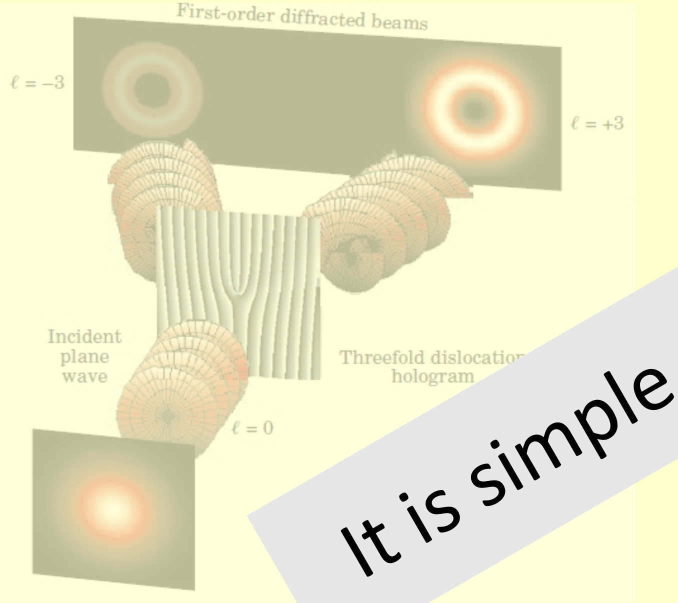


Holograms

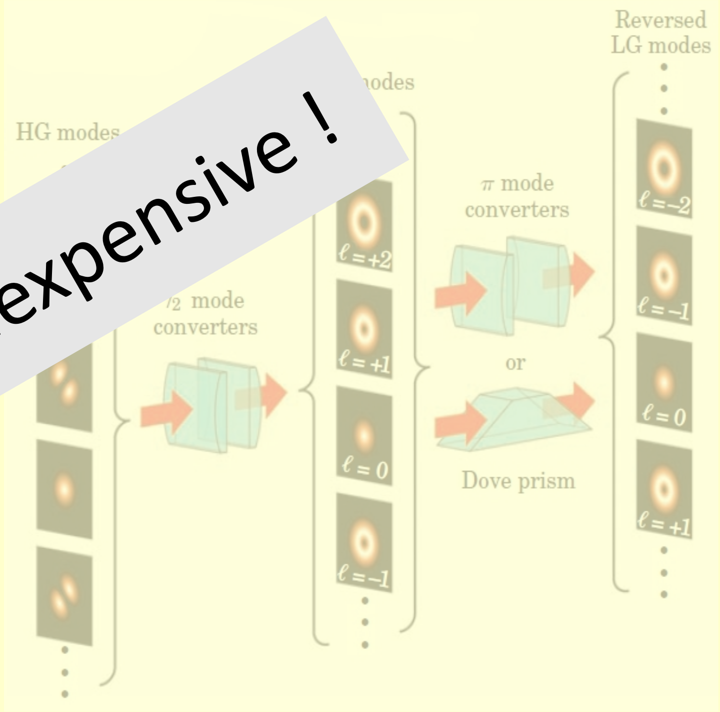


Cylindrical lenses

Generation of paraxial optical-vortex beams



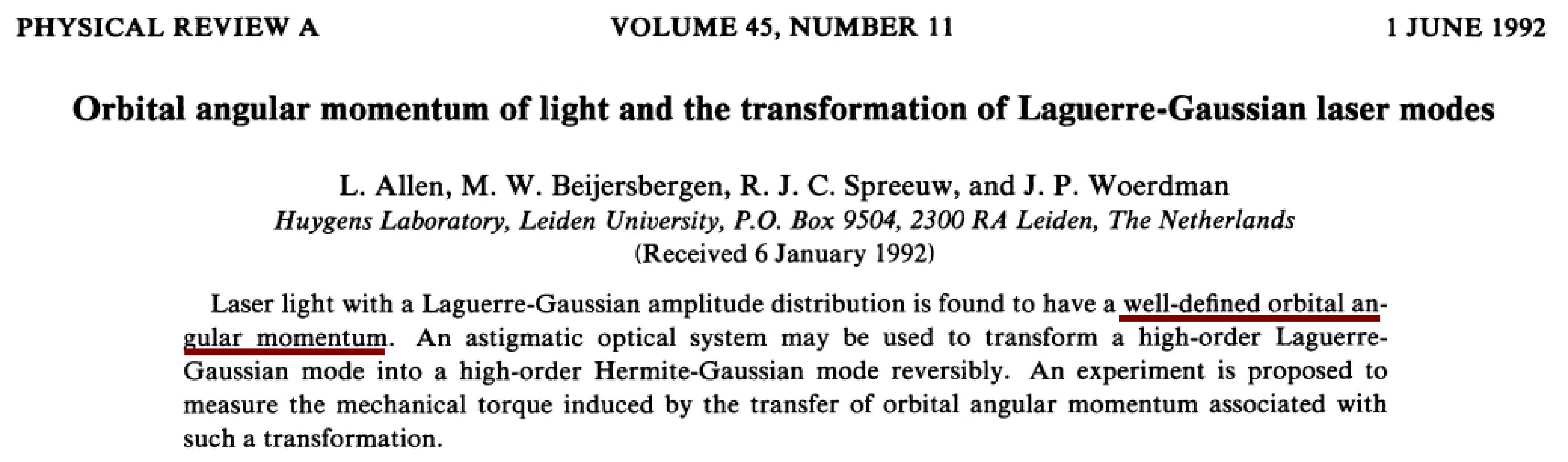
Holograms



Cylindrical lenses

It is simple and inexpensive !

Research in optical-vortex light



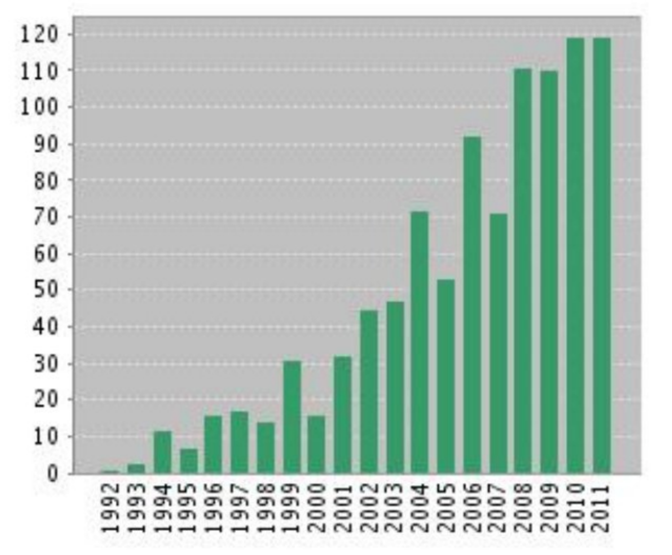
PHYSICAL REVIEW A VOLUME 45, NUMBER 11 1 JUNE 1992

Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes

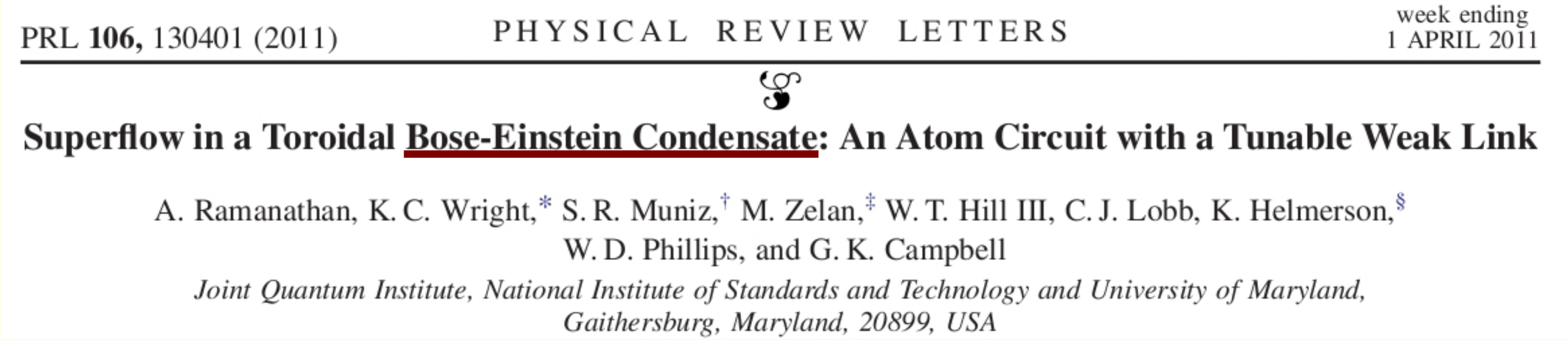
L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman
Huygens Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands

(Received 6 January 1992)

Laser light with a Laguerre-Gaussian amplitude distribution is found to have a well-defined orbital angular momentum. An astigmatic optical system may be used to transform a high-order Laguerre-Gaussian mode into a high-order Hermite-Gaussian mode reversibly. An experiment is proposed to measure the mechanical torque induced by the transfer of orbital angular momentum associated with such a transformation.



It rapidly extended to many areas...



PRL **106,** 130401 (2011) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2011

Superflow in a Toroidal Bose-Einstein Condensate: An Atom Circuit with a Tunable Weak Link

A. Ramanathan, K. C. Wright,[*] S. R. Muniz,[†] M. Zelan,[‡] W. T. Hill III, C. J. Lobb, K. Helmerson,[§]
W. D. Phillips, and G. K. Campbell
Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland,
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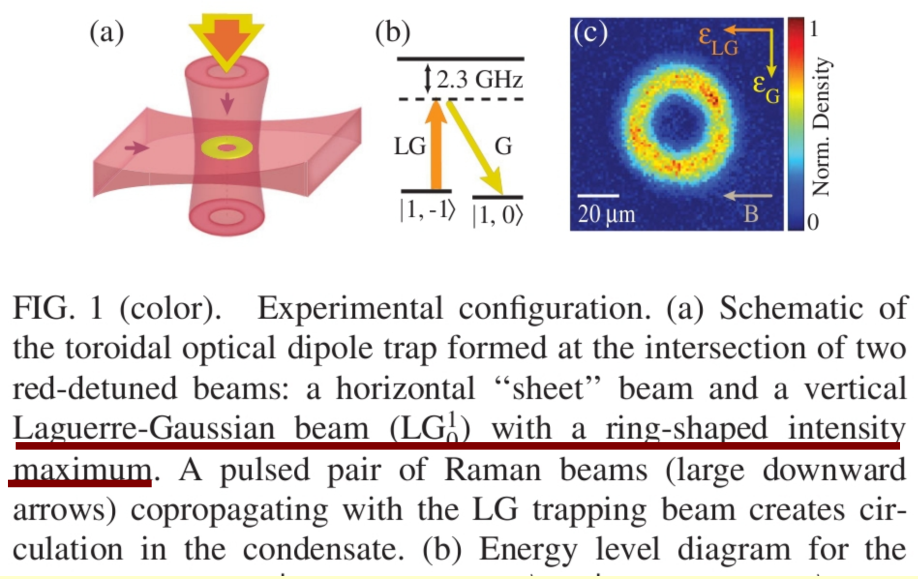
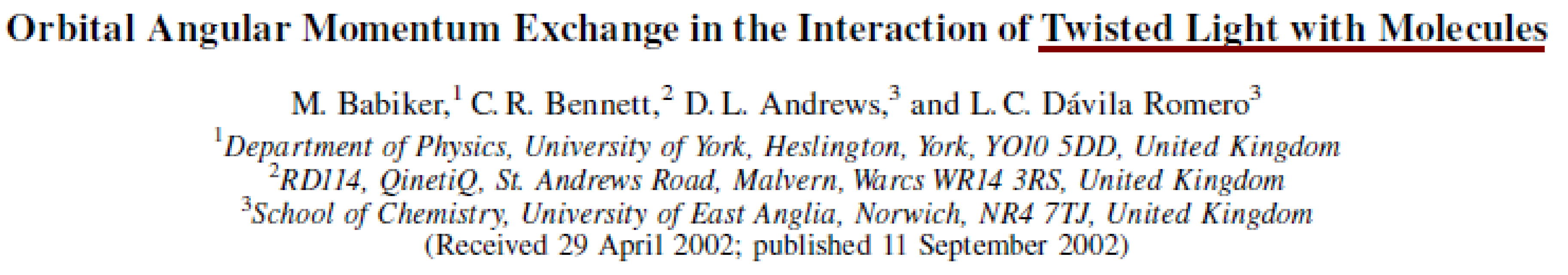


FIG. 1 (color). Experimental configuration. (a) Schematic of the toroidal optical dipole trap formed at the intersection of two red-detuned beams: a horizontal "sheet" beam and a vertical Laguerre-Gaussian beam (LG_0^1) with a ring-shaped intensity maximum. A pulsed pair of Raman beams (large downward arrows) copropagating with the LG trapping beam creates circulation in the condensate. (b) Energy level diagram for the

Research directions



Orbital Angular Momentum Exchange in the Interaction of Twisted Light with Molecules

M. Babiker,[1] C. R. Bennett,[2] D. L. Andrews,[3] and L. C. Dávila Romero[3]
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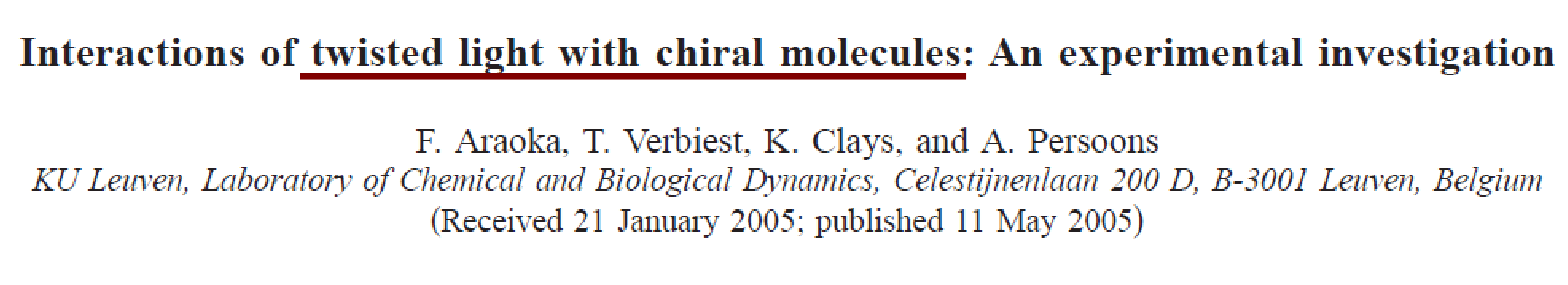

Interactions of twisted light with chiral molecules: An experimental investigation

F. Araoka, T. Verbiest, K. Clays, and A. Persoons
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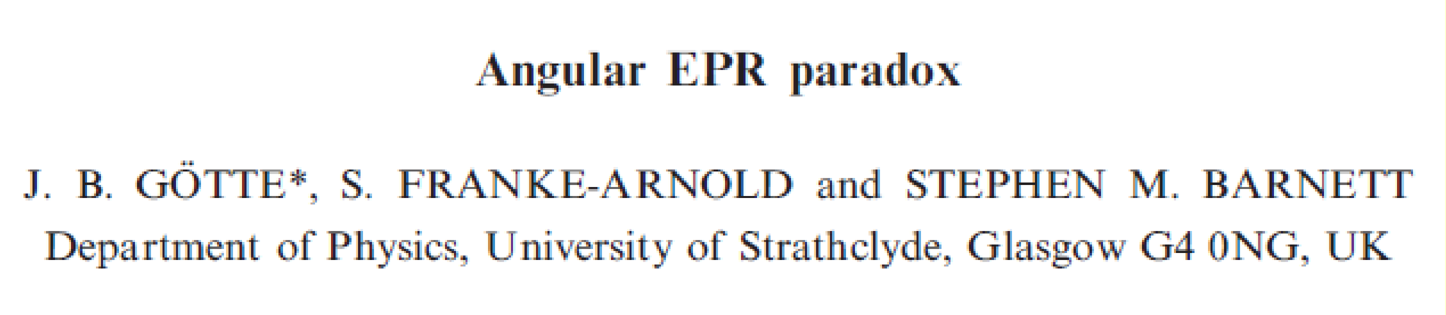
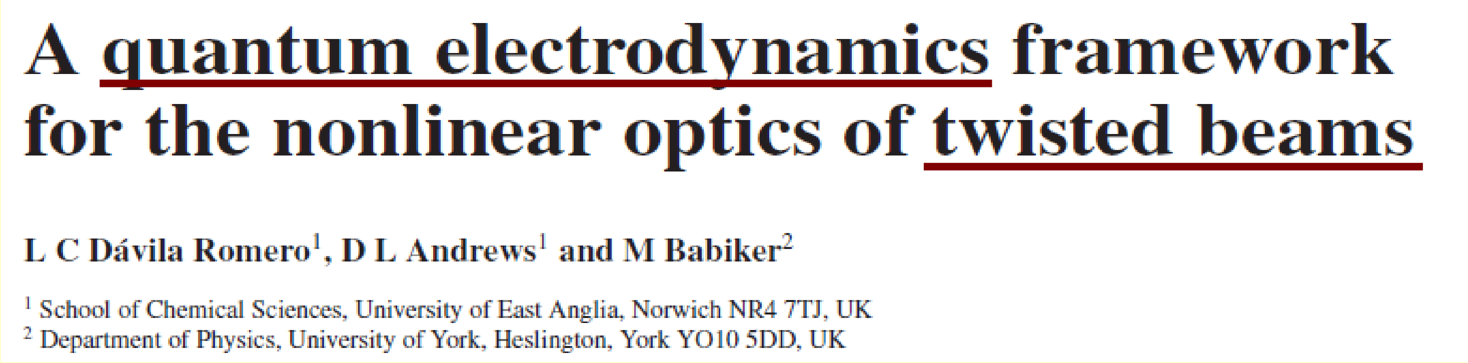
(Received 21 January 2005; published 11 May 2005)

Research directions



Angular EPR paradox

J. B. GÖTTE*, S. FRANKE-ARNOLD and STEPHEN M. BARNETT
Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK



A quantum electrodynamics framework for the nonlinear optics of twisted beams

L C Dávila Romero[1], D L Andrews[1] and M Babiker[2]

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Screw-Shaped Light in Extended Electromagnetics

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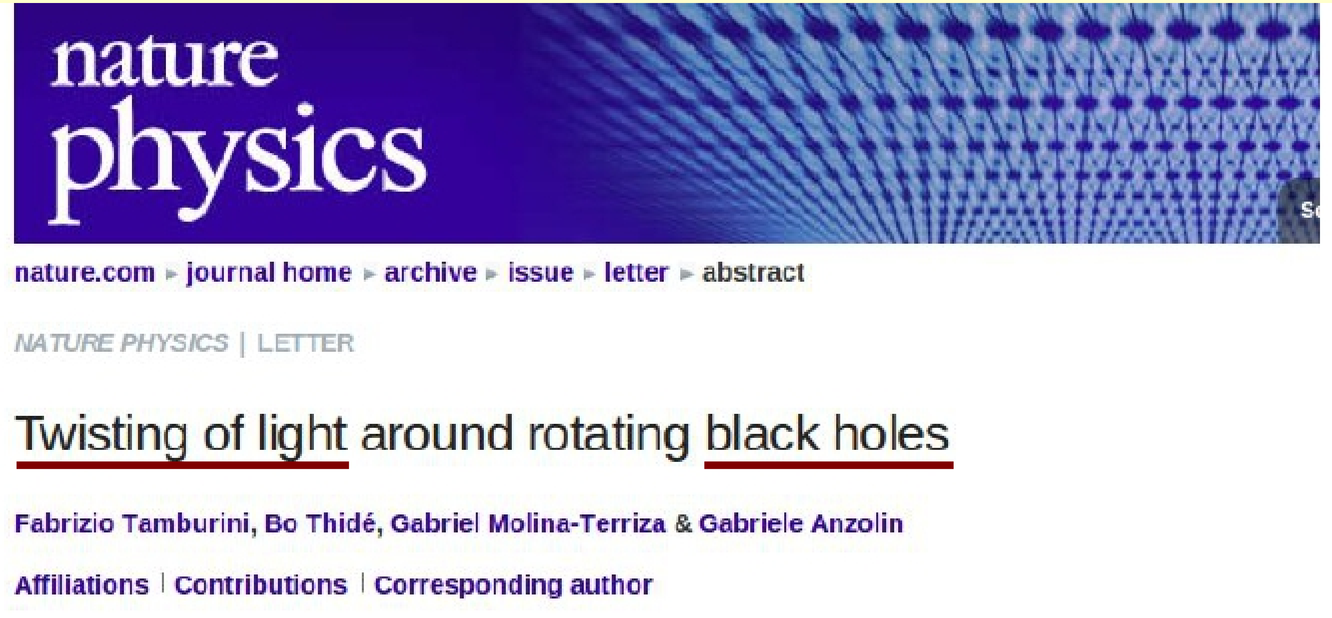
Research directions



nature physics

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NATURE PHYSICS | LETTER

Twisting of light around rotating black holes

Fabrizio Tamburini, Bo Thidé, Gabriel Molina-Terriza & Gabriele Anzolin

Affiliations | Contributions | Corresponding author

Research directions

WEEKLY | NEWS IDEAS INNOVATION

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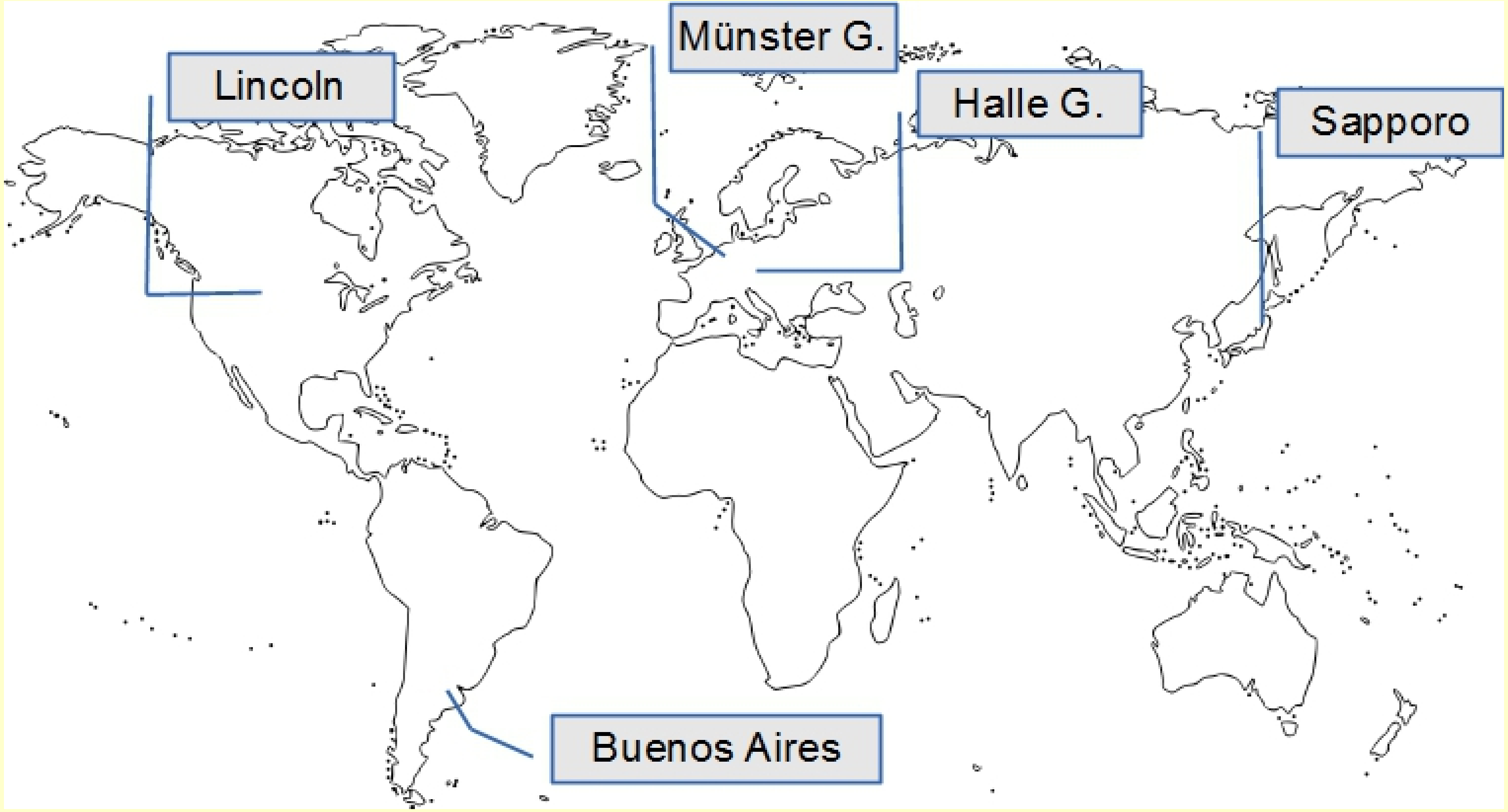
Optical-vortex light and Semiconductors

Papers published only after 2008 … still only few groups



New effects were predicted

Paraxial beams:

- creation of circular electric currents
- generation of local and ultrafast magnetic fields
- new transitions in quantum dots

New effects were predicted

Paraxial beams:

- creation of circular electric currents
- generation of local and ultrafast magnetic fields
- new transitions in quantum dots

Non-paraxial beams:

- strong magnetic interactions
- excitation of intersubband states in quantum wells
- excitation of light holes in quantum dots

I will talk about

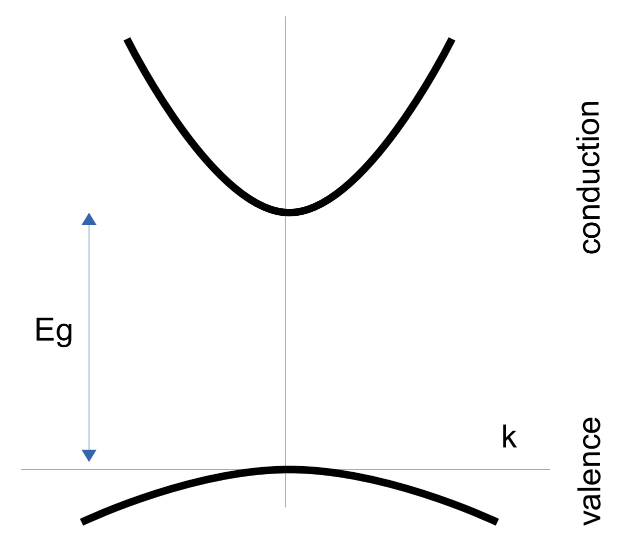
- How to write the interaction Hamiltonian for OVs

- circular electric currents in bulk and quantum rings
  (paraxial physics)

- new transitions in quantum dots for heavy and light holes
  (non-paraxial physics)

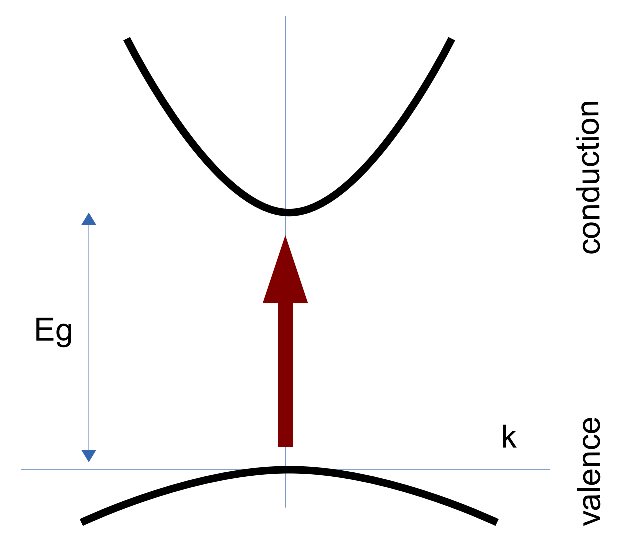
A short review on semiconductor optics

Bulk semiconductors $\varphi(\bar{r}) = e^{i\bar{k}\bar{r}} u_b(\bar{r})$



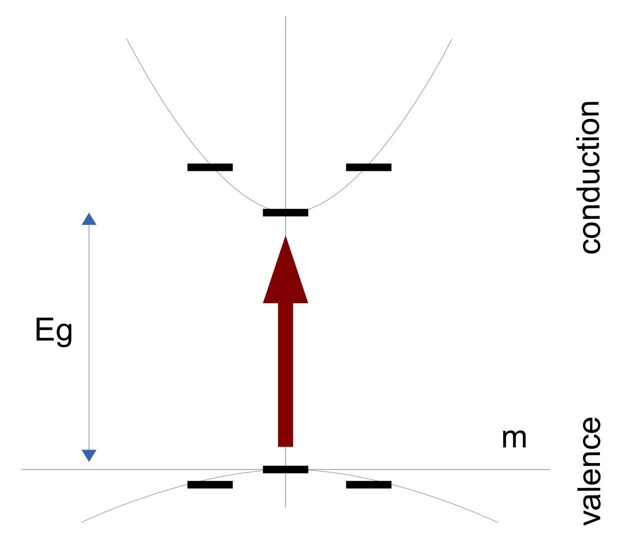
Simplified two-band model

Bulk semiconductors $\varphi(\bar{r}) = \mathrm{e}^{i\bar{k}\bar{r}} u_b(\bar{r})$



Normal light causes vertical transitions

Semiconductor quantum dot $\varphi(\bar{r})=G(r)\,\mathrm{e}^{im\varphi}u_b(\bar{r})$



Transitions between discrete energy levels

Interaction Hamiltonian at r = 0
How to model it ?

Use minimal coupling:

$$H = \frac{1}{2m}\left[\overline{p} + q\,\overline{A}(\overline{r})\right]^2 + U(\overline{r}) + V(\overline{r})$$

It is perfectly safe to use the vector potential, but some people prefer to use electric and magnetic fields.

Interaction Hamiltonian

One can try a gauge transformation:

$$\begin{gathered}\overline{A}(\overline{r})\rightarrow\overline{A'}(\overline{r})\\ U(\overline{r})\rightarrow U'(\overline{r})\end{gathered}$$

that resembles the dipole-moment approximation.
Then:

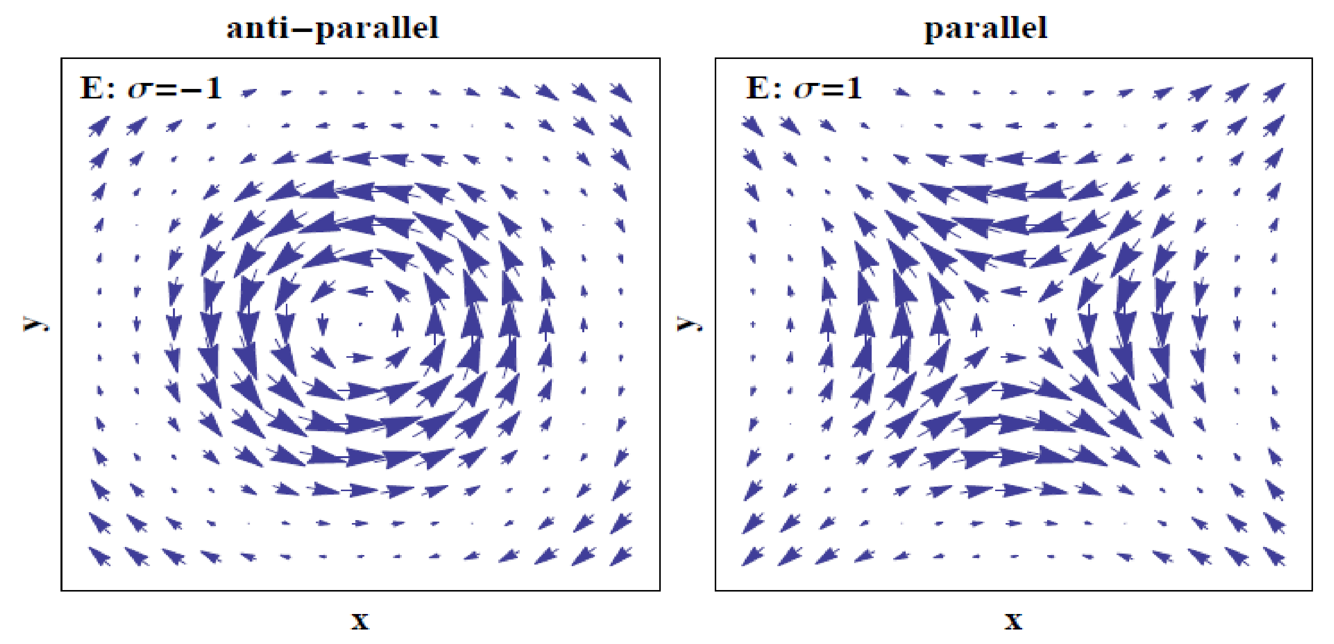
$$H=\frac{\overline{p}^{2}}{2m}+V(\overline{r})+\overbrace{\frac{q}{|\ell|+1}\overline{r}\cdot\overline{E}(\overline{r})}^{\textit{Electric multipolar term}}+\underbrace{T(\overline{B})}_{\textit{Magnetic term}}$$

Near the phase singularity, we cannot in general disregard the magnetic term !

When is E>>B ?

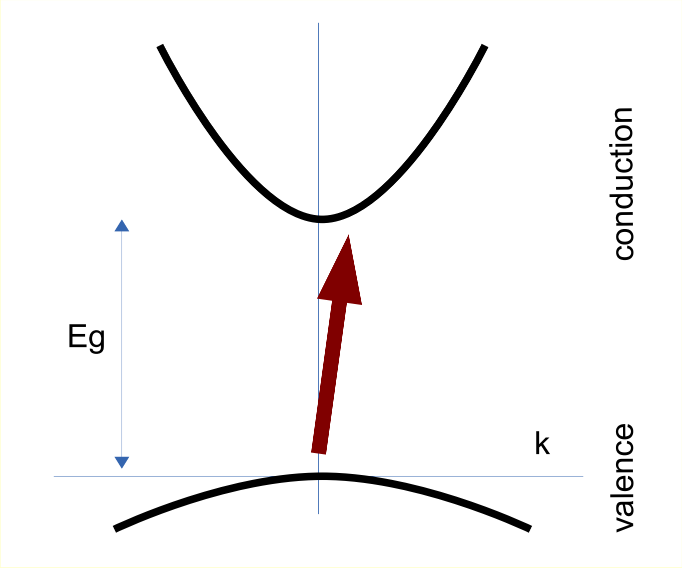
Magnetic fields of optical-vortex are always smaller than electric fields when Sign(ℓ)=Sign(σ):

$$H=\frac{\bar{p}^2}{2m}+V(\bar{r})+\frac{q}{|\ell|+1}\bar{r}\cdot\bar{E}(\bar{r})$$



Currents in Bulk

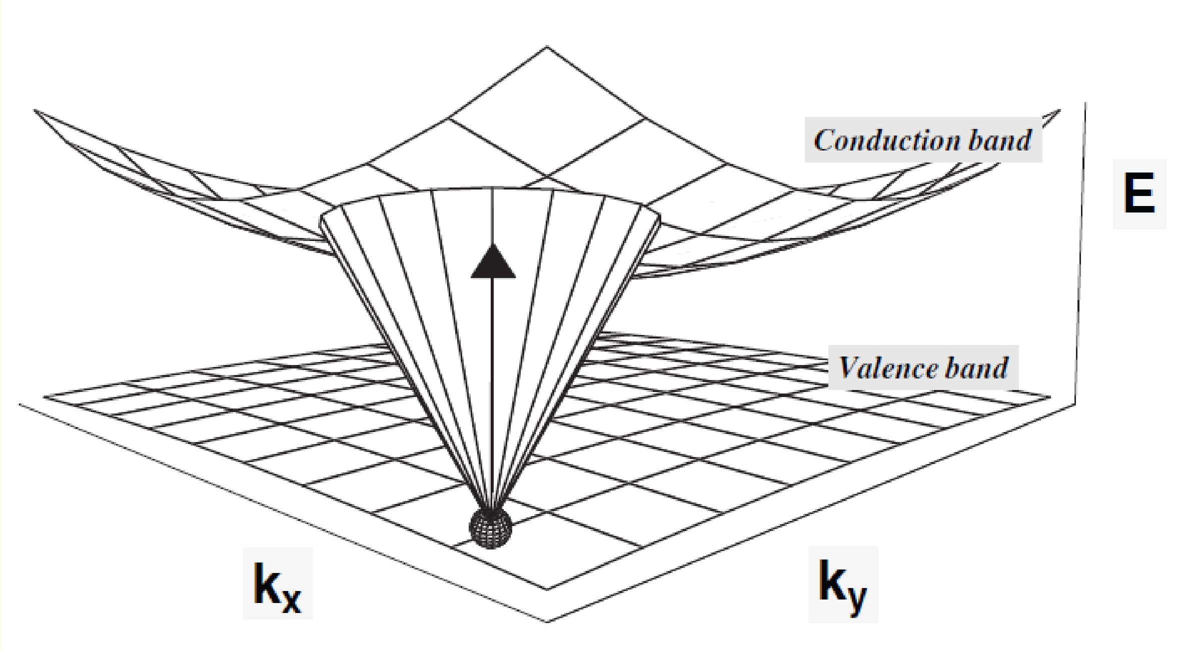
Apologies for a tiny lie …
plane waves produce *almost* vertical transition



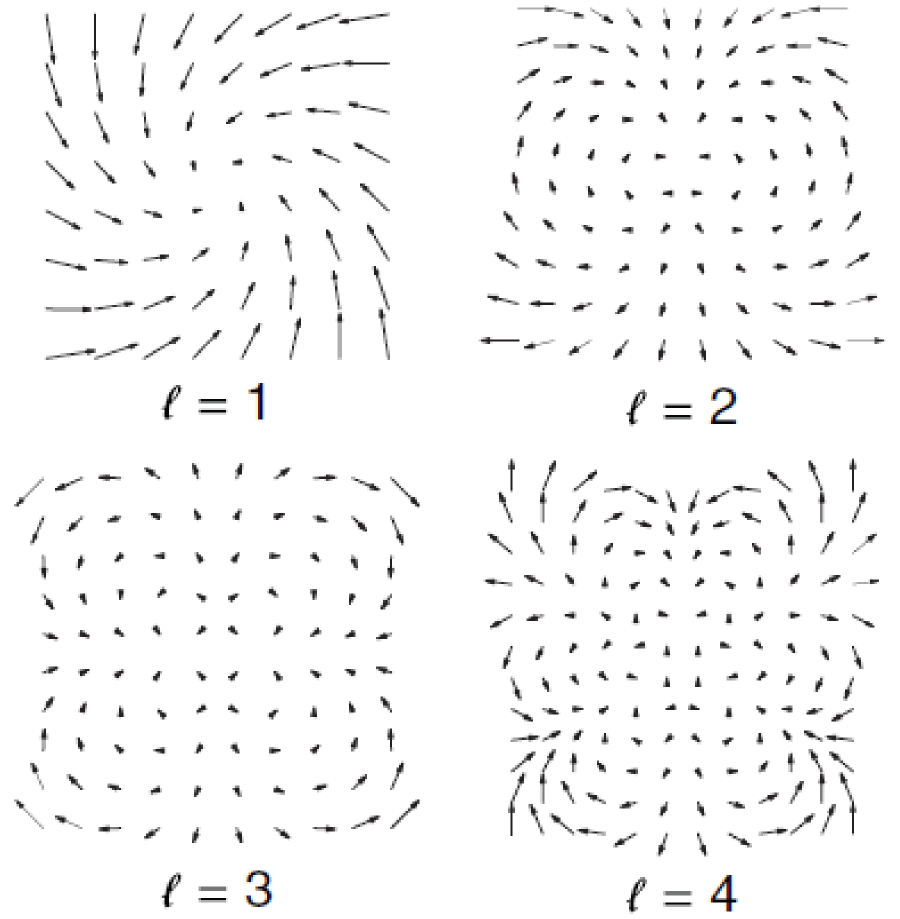
The momentum of light is transferred to the electron

The transition is simple for symmetry reasons

Optical-vortices have cylindrical symmetry, and they excite a superposition of electron states in the conduction band



Formation of complex patterns of electric currents



$\ell = 1$

$\ell = 2$

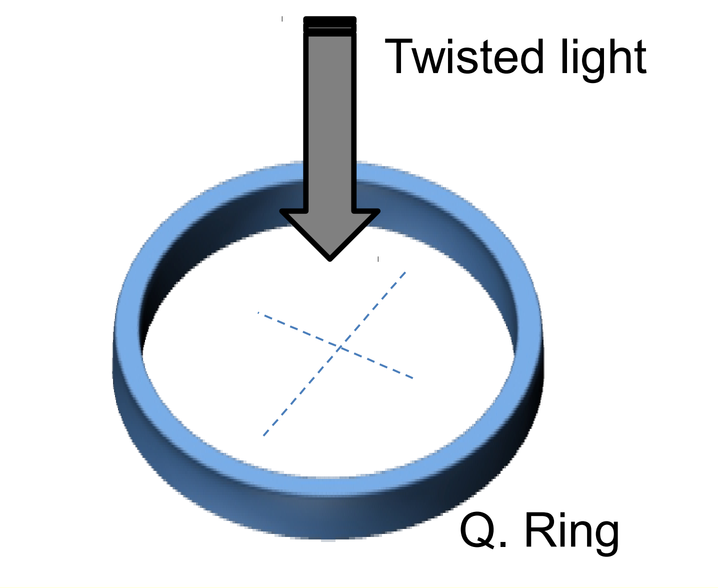
$\ell = 3$

$\ell = 4$

Currents in quantum rings

Quantum rings are 1D structures with the same symmetry as the optical-vortex

$$\varphi_m(\bar{r}) = \frac{1}{\sqrt{2\pi}} e^{im\varphi} u_b(\bar{r})$$



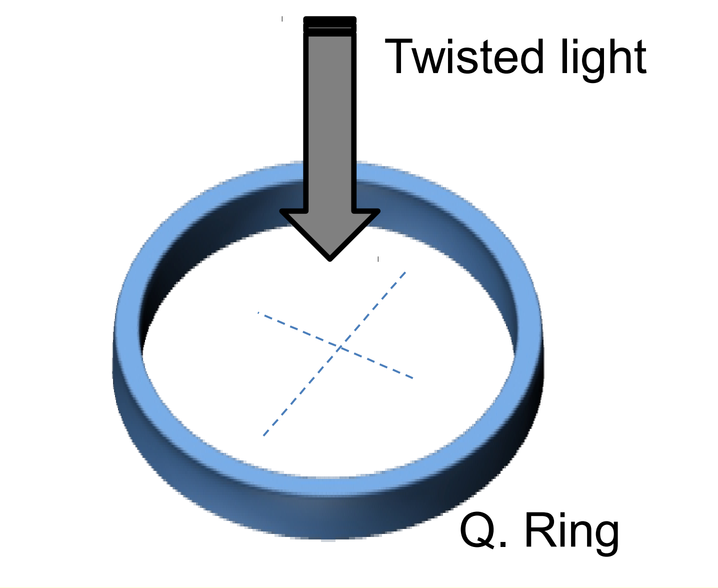
Currents in quantum rings

Quantum rings are 1D structures with the same symmetry of the optical-vortex

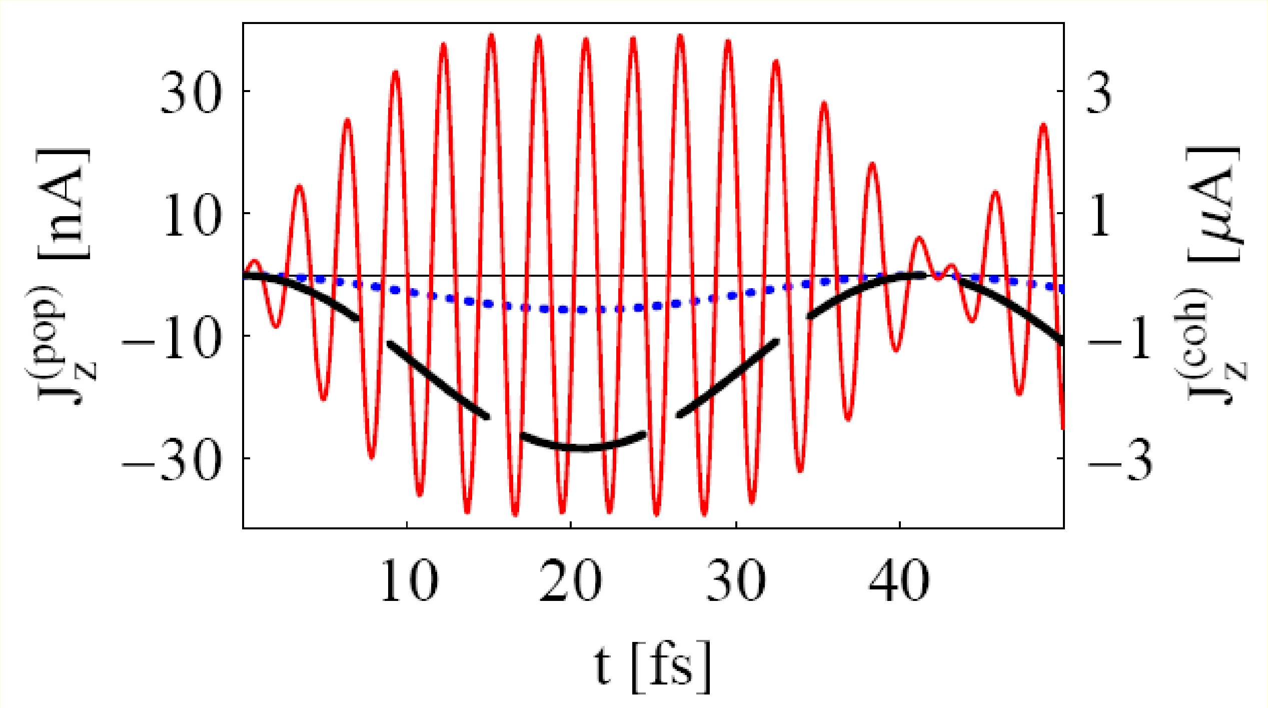
$$\varphi_m(\bar{r}) = \frac{1}{\sqrt{2\pi}} e^{im\varphi} u_b(\bar{r})$$

$$\varphi_m(\bar{r}) \xrightarrow{H} \varphi_{m+\ell}(\bar{r})$$

No superposition of states !



Induced electric current

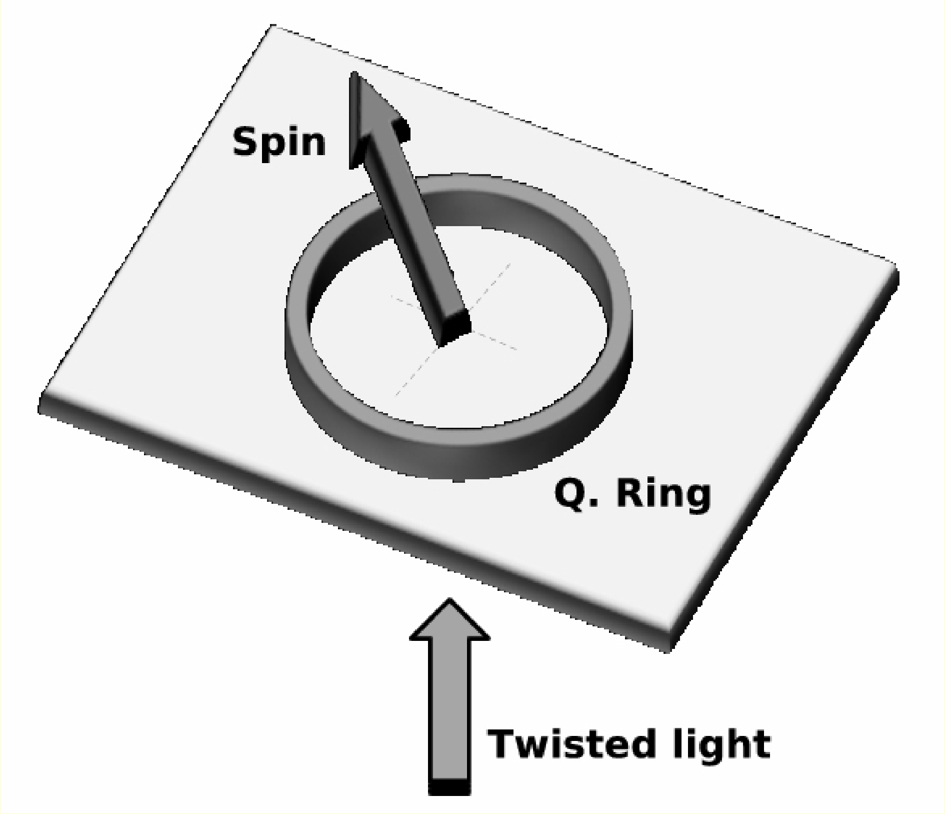


Two contributions:

A : coherence

A^2 : population

A possible application

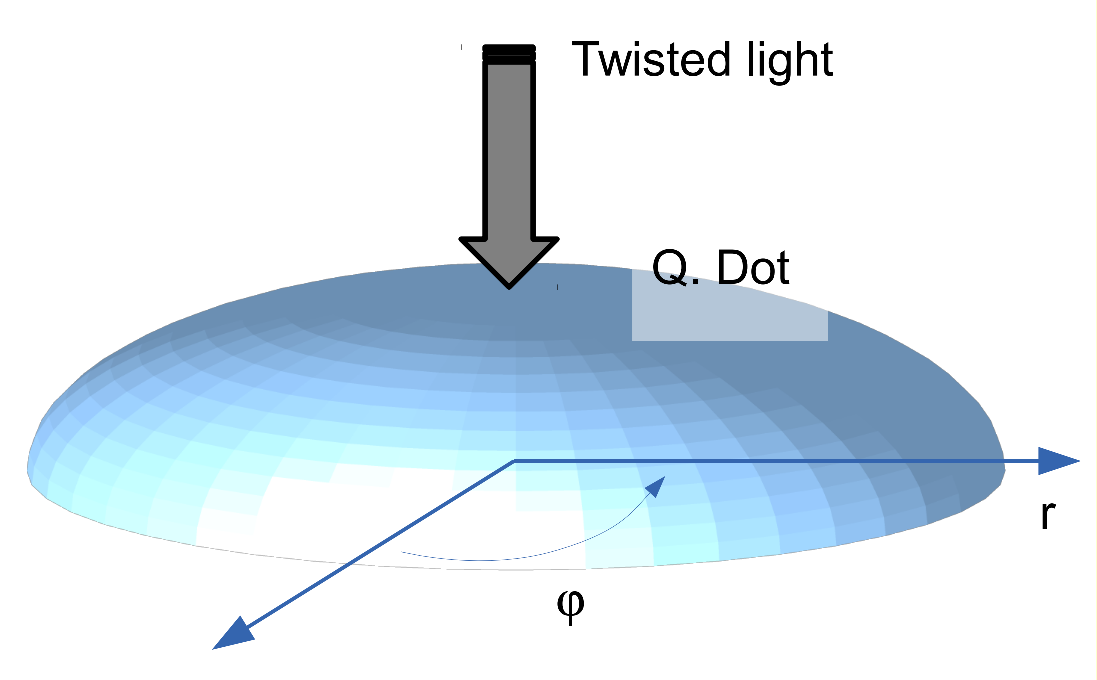


One or a stack of quantum rings may control a spin

Heavy-hole transitions in Quantum Dots

Disk-shape quantum dot with parabolic confinement excited by a paraxial beam(only in-plane E field)

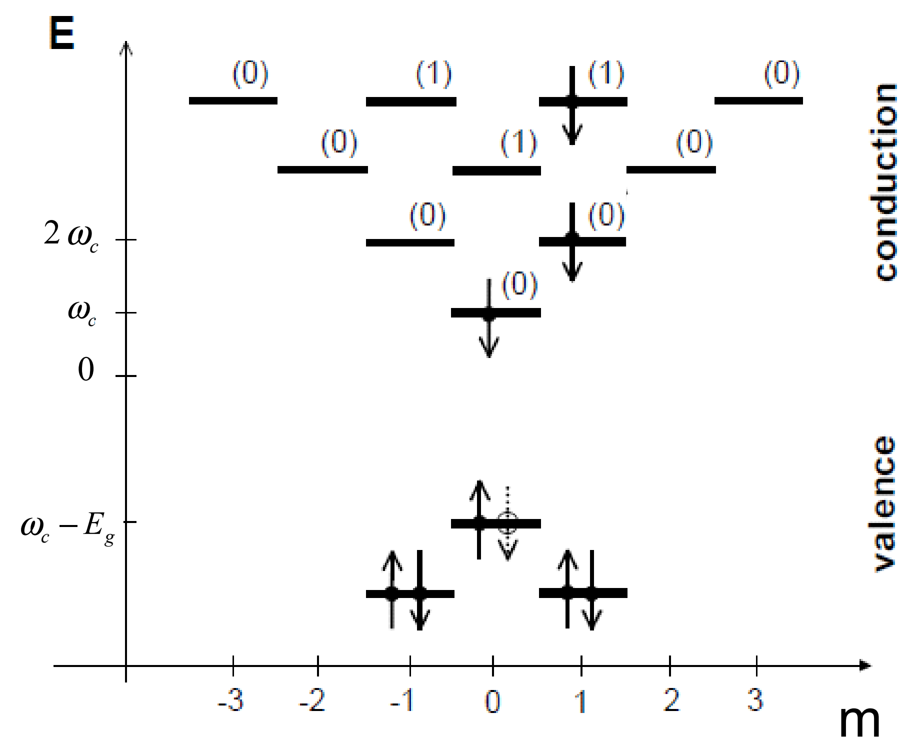
$$\varphi(\bar{r}) = G(r)\,\mathrm{e}^{im\varphi}\,u_b(\bar{r})$$



Transition matrix elements:

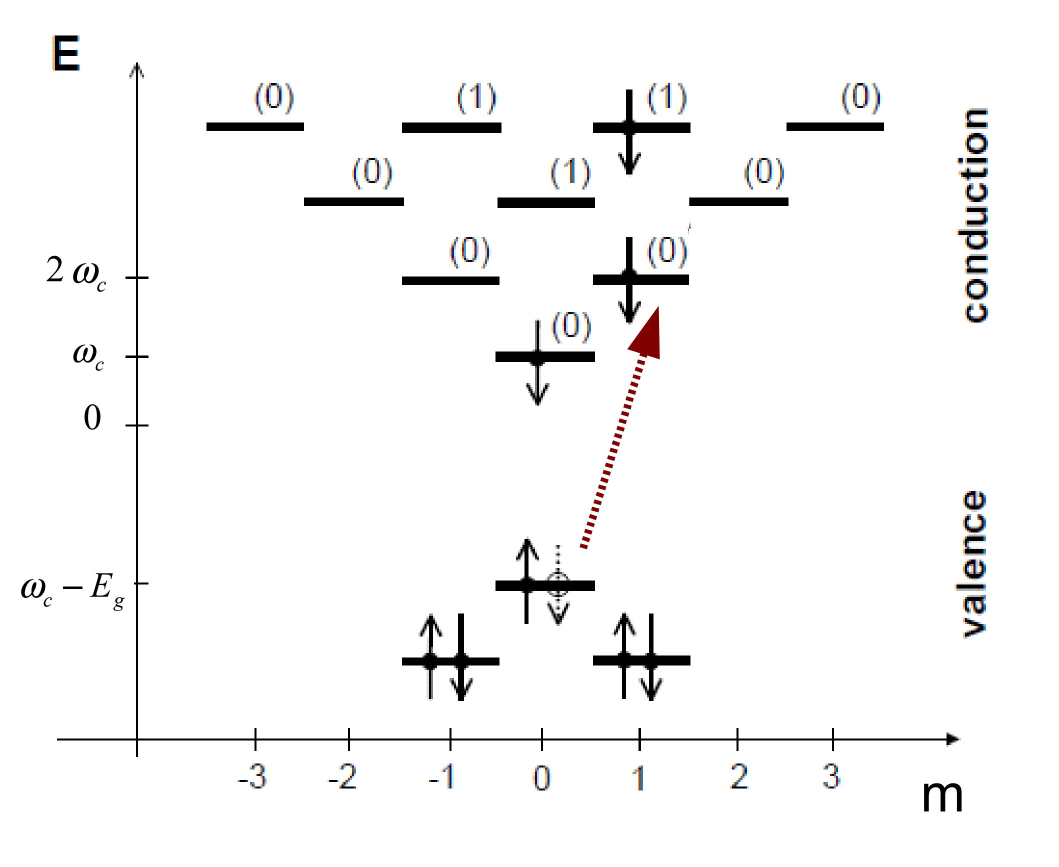
$$\left|\left\langle c\, s'\, m' \middle| H_I \middle| v\, s\, m \right\rangle\right| \propto \delta_{\ell-(m'-m)}\, h(\zeta)$$

(c) conduction band
(v) valence band
(m) orbital quantum #
(s) radial quantum #
(ζ) QD size / beam waist



(#) radial quantum number
m orbital quantum number

Twisted light



(#) radial quantum number
m orbital quantum number

Light-hole transitions in Quantum Dots

$$|3/2,+1/2\rangle = -\frac{1}{\sqrt{6}}[(|p_x\rangle + i|p_y\rangle)\downarrow -2|p_z\rangle\uparrow]$$

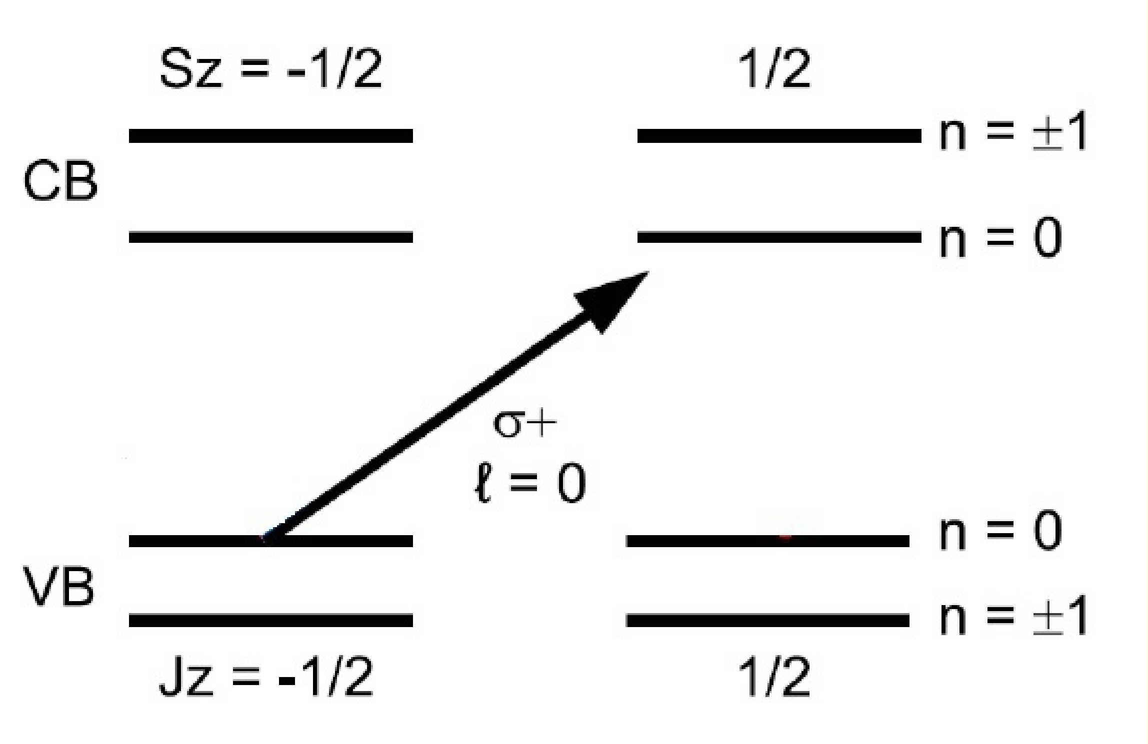
$$|3/2,-1/2\rangle = \frac{1}{\sqrt{6}}[(|p_x\rangle - i|p_y\rangle)\uparrow +2|p_z\rangle\downarrow]$$

Non-paraxial optical vortex

$$\begin{aligned}
E_x(\mathbf{r},t) &= \frac{E_0}{2}(q_r r)\sin(\omega t - q_z z - \varphi) \\
E_y(\mathbf{r},t) &= \frac{E_0}{2}(q_r r)\cos(\omega t - q_z z - \varphi) \\
E_z(\mathbf{r},t) &= -E_0\frac{q_r}{q_z}\cos(\omega t - q_z z)
\end{aligned}$$

Transitions in dots

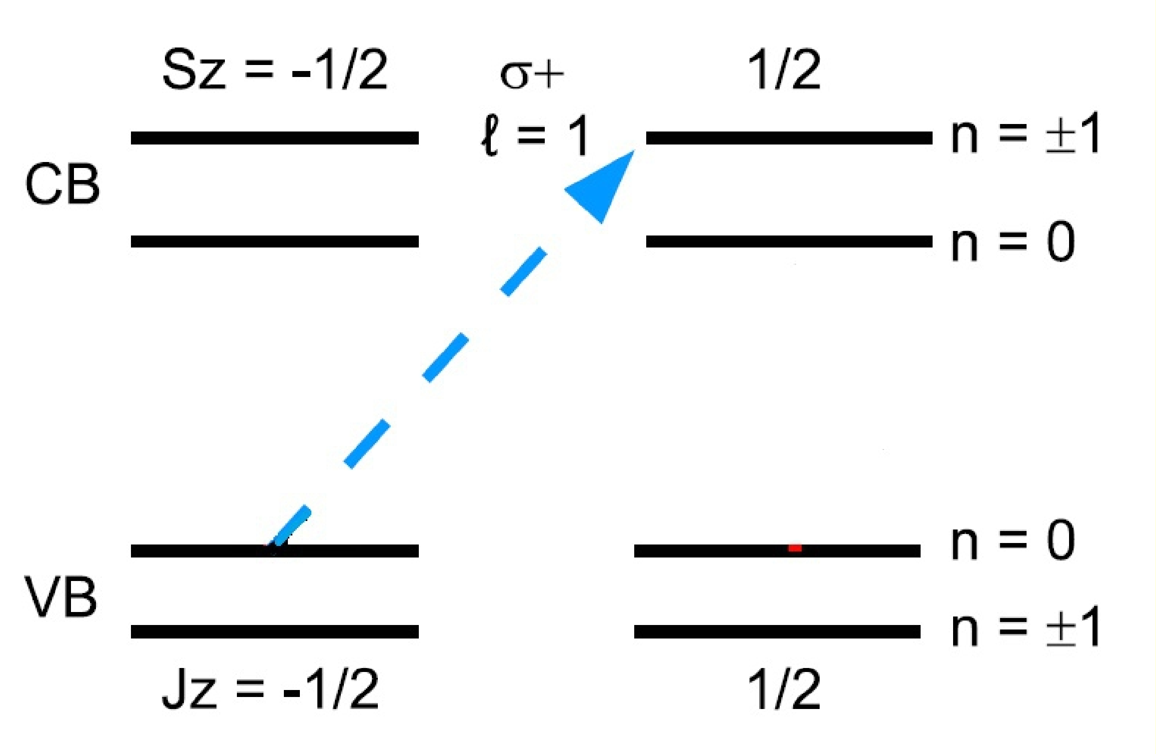
$$|3/2,-1/2\rangle = \frac{1}{\sqrt{6}}\boxed{[(|p_x\rangle - i|p_y\rangle)\uparrow}+2|p_z\rangle\downarrow]$$



Plane waves

Transitions in dots

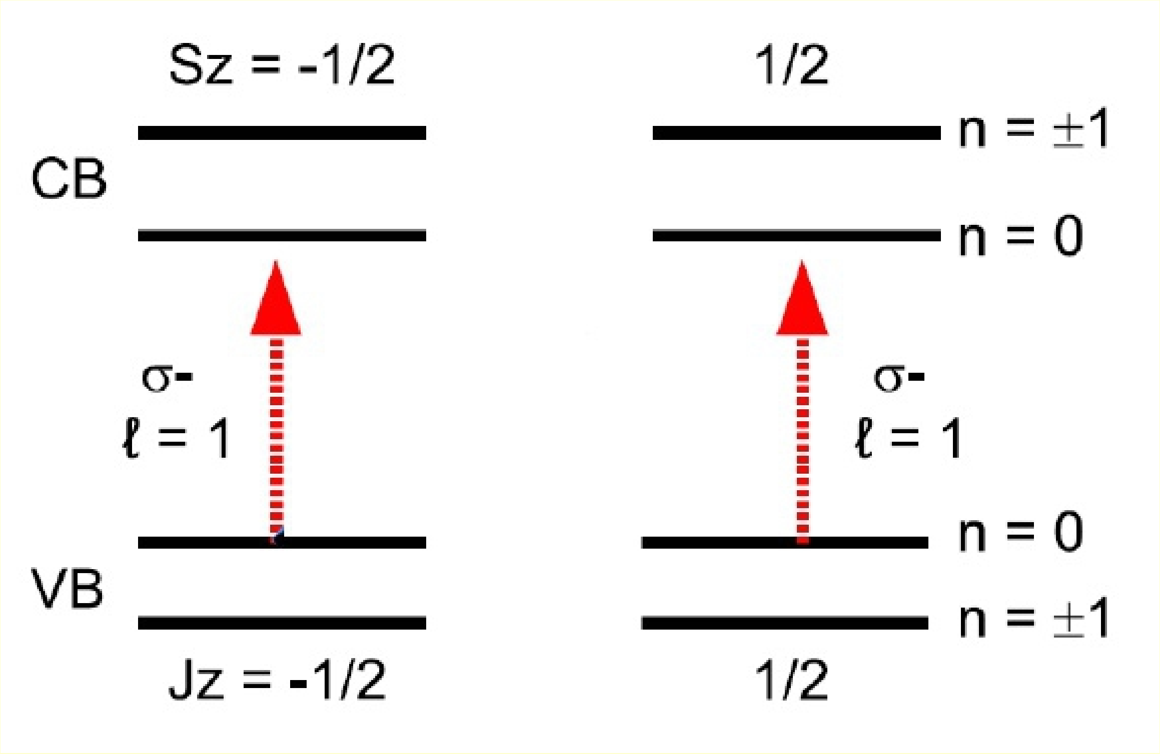
$$|3/2,-1/2\rangle = \frac{1}{\sqrt{6}}\boxed{[(|p_x\rangle - i|p_y\rangle)\uparrow}+2|p_z\rangle\downarrow]$$



Opt. vortex

Transitions in dots

$$|3/2,-1/2\rangle = \frac{1}{\sqrt{6}}[(|p_x\rangle - i|p_y\rangle)\uparrow \boxed{+2|p_z\rangle \downarrow]}$$



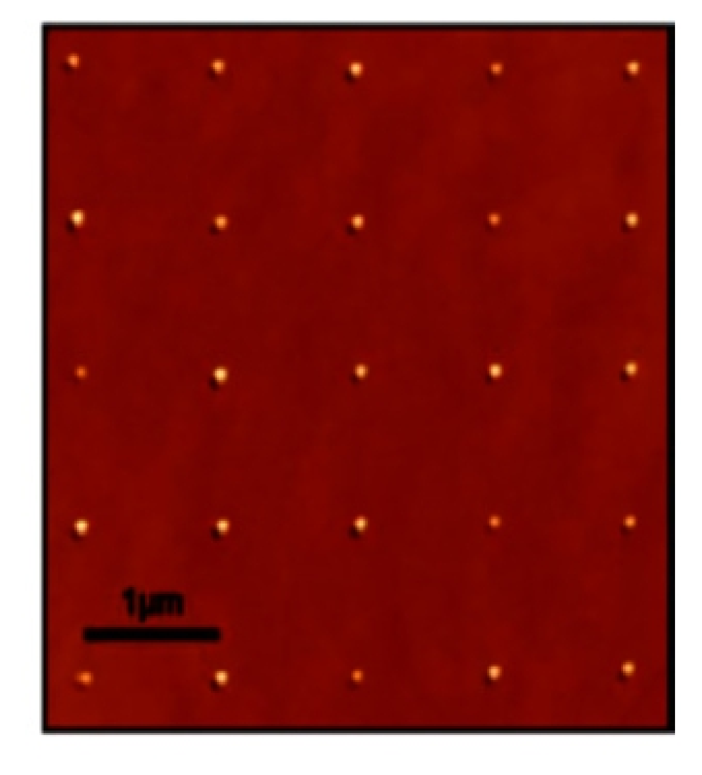
Opt. vortex

A possible application

Quantum computing

- scalability
- optical control of each QD

use the z-component of a focused non-paraxial optical vortex



SEM-micrograph of site-controlled InAs QDs.

Rep. Prog. Phys. **76** (2013) 092501

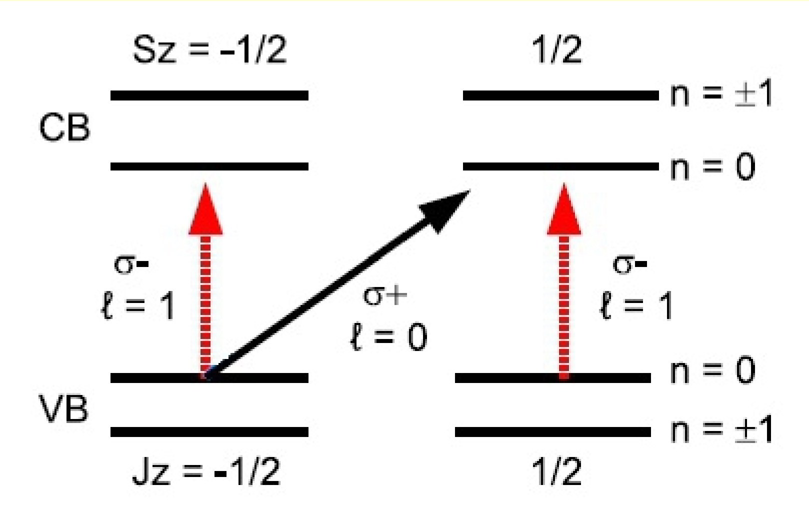
… the non-paraxial beam σ=-1, ℓ=1:

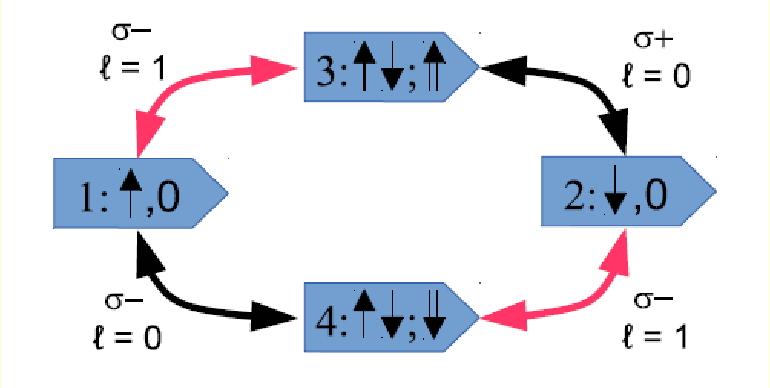
$$E_z(\mathbf{r},t) = -E_0\frac{q_r}{q_z}\cos(\omega t - q_z z)$$

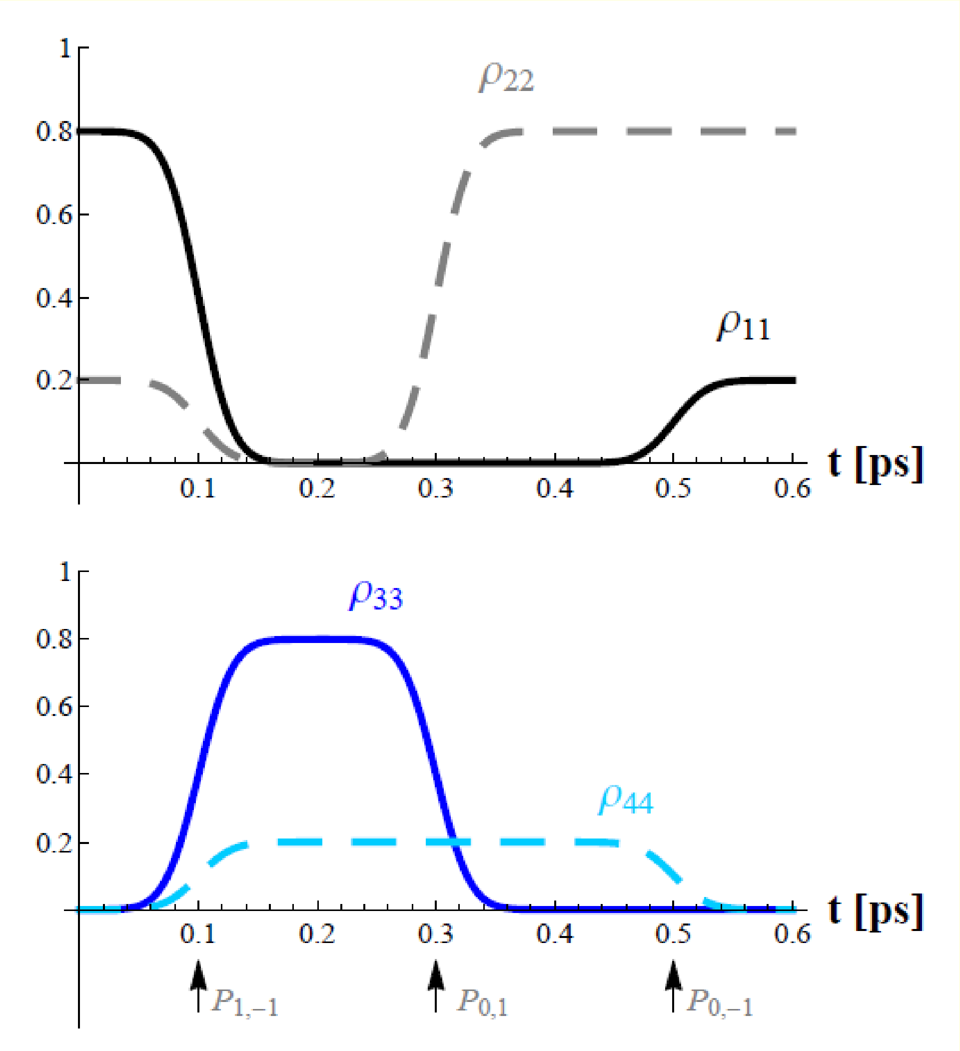
plus a plane wave σ=+1, ℓ=0:

$$\begin{aligned} E_x(\mathbf{r},t) &= \frac{E_0}{2}\sin(\omega t - q_z z) \\ E_y(\mathbf{r},t) &= \frac{E_0}{2}\cos(\omega t - q_z z) \end{aligned}$$

Transitions in dots







Spin flip in less than a picosecond at normal incidence

Conclusions

The interaction of Optical Vortex with semiconductor brings about many new effects, such as

- B field may overcome E field interaction
- direct generation of circular electric currents
- extended control of electronic transitions in QDs

Obrigado pela atenção !